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Addressing the challenges of ECMO simulation

Introduction

Extracorporeal Life Support (ECLS) options such as Extracorporeal Cardio Pulmonary Resuscitation (E-CPR) and Extracorporeal Membrane Oxygenation (ECMO) are interventions initiated on patients whose lives are in danger due to pulmonary or cardiac failure. The initiation of ECLS is time critical and so is the ongoing management as any issue during the therapy can irreversibly compromise the patient outcome.

There are many ways of defining and calculating survival rates post-ECMO. In general, reported Venous-Venous ECMO (VV-ECMO) patient survival rates range between 50% and 70% for adult patients (1) and 54% (2, 3) and 64% (4) for paediatric patients, whereas in the case of Venous-Arterial ECMO (VA-ECMO) for adult and paediatric patients, the current statistics are respectively between 42% (5) and 60% (6, 7), and 50% (3, 8) and 62%.(9) The high-risk nature of placing a patient on ECMO is simply accepted as it is a potentially life-saving procedure that buys time to the patients for the healing process of their diseased organ(s) or ultimate therapy to take place. Commonly reported fatal or life-threatening complications associated with ECMO in adult and paediatric patients include bleeding, oxygenator failure, haemolysis, leg ischaemia, venous thrombosis, and central nervous system complications.(10) Several factors affect the potential patient outcome, such as the patient's physical and physiological resilience and condition, in addition to the effectiveness of the multidisciplinary clinical team looking after the ECMO patient. Their goal is to prevent complications and respond promptly to any potential emergency situation. Due to the maturity of ECMO as well established and documented procedures, it is now important to develop and adopt better processes with regards to human factors skills acquisition for the multidisciplinary team looking after those patients and to consider the aspects of credentialing, recertification, and continuing ECMO education of the clinical team.

Human factor aspect of high-level performing clinical teams

The patients' condition and high-risk nature of ECMO therapy force health care services to ensure clinicians are properly trained and ready to effectively deal with critical situations. Although ECMO training guidelines have been developed by the Extracorporeal Life Support Organization (ELSO), there is still no formal ECMO credentialing process in place.(11, 12) In addition, there is relatively strong evidence showing that hospitals with higher numbers of ECMO cases tend to achieve better patient outcomes.(13, 14) This can be partly explained by the fact that the clinicians in hospitals

managing higher numbers of ECMO patients gain more ECMO exposure and experience, which in turn helps fine-tune and retain their skill-set.

Various models of ECMO team structure exist and have been adopted based on organisational culture, number of ECMO cases managed, and scope of practice or skill-set of the clinicians forming the team. A communality of ECMO teams is that they are multiprofessional and generally include nurses, physicians (intensivist and/or surgeons), respiratory therapists, perfusionists, pharmacists, and sometimes critical care practitioners or paramedics.(15-18) They are all specialised in their own field and play a well-defined and critical role in ensuring the best possible outcome of ECMO patients thanks to their complementary skills. However, there are also common cognitive and practical skills expectations from them so most emergency situations can be dealt with safely and effectively.(19) The teaching and practice of overlapping cognitive and practical skills promotes better understanding and anticipation of each other’s decisions and actions in a critical or emerging situation which could help save valuable time and hence enhance patient safety.

ECMO issues are time-critical emergencies for the patient and require quick actions that themselves rely on optimally coordinated teamwork, effective communication, planning, decision making, standard operating procedures, and well-defined guidelines. For example, the proximity of additional resources and equipment and clear guidance and experience on what to do in a given situation, sometimes with the help of cognitive aids, can make a difference between life and death for a patient. These key recommendations and many other relevant ones are derived from Crisis Resource Management (CRM) principles and help ensure the quality of an ECMO programme.(19) Human factors and CRM principles are important elements of high-level performing teams which are expected to provide high reliability results such as the teams of technicians and engineers supporting Formula 1 drivers and achieving record breaking pit stop times. Similarly high-risk industries depend on high-reliability teams and they ensure the safety of their activity and personnel through regular and specific human factors and CRM training, often through simulation.(20) There is evidence of the benefits of CRM training in the aviation industry where it has been seen to improve crew members’ reactions, attitudes, and behaviours(21). Although, it is still difficult to determine exactly what impact it has on aviation safety as many other aspects of the industry have also evolved in parallel to the growing use of simulation as a training approach.(21) From a healthcare point of view, commonly listed CRM principles are shown in Table 1 under the key headings of “decision making and teamwork” and “resource management”.(22) These are some of the key ingredients at the disposal of high-level performing clinical teams to prevent or manage ECMO-related crisis situations. For example, ongoing assessment of the patient, regular recording of multiple parameters, and monitoring of circuit pressures answer to the point of “re-evaluate repeatedly”. Keeping sets of circuit clamps on the ECMO machine trolley and having a pre-primed circuit ready at all times demonstrate “anticipate and plan”, while “use of cognitive aids” refers to checklists and cards listing the steps to respond to various ECMO emergencies .

Decision making	Teamwork and resource management
Know the environment	Call for help early
Anticipate and plan	Exercise leadership and fellowship
Use all available information	Distribute the workload

Prevent and manage fixation errors	Mobilize all available resources
Cross (double) check	Communicate effectively
Use cognitive aids	Use good teamwork/Mutual support
Re-evaluate repeatedly	
Allocate attention wisely	
Set priorities dynamically	

Table 1: Key Crisis Resource Management principles of high-level performing clinical teams adapted from Rall and Dieckmann (22)

Simulation-based education (SBE), from the simplest approaches to the most immersive modalities helps promote optimum individual and team performance especially when it is complemented by appropriate debriefing techniques(23), but is still in its infancy in the domain of ECMO as many aspects can still be much improved in terms of realism. As in many other clinical domains, ECMO simulation has great potential in terms of competency assessment and is already used in different places to that effect. Although still in its infancy, summative assessment of ECMO specialists using simulation has been reported to be used by 63% (n=59) of ELSO centres in the US responding to a 2017 survey.(24) This is based on a 62% response rate (n=94) out of 151 centres invited to participate. This demonstrates the recognised need for a high level of competency on the part of the ECMO specialists and the value of simulation in evaluating performance levels that goes beyond basic skills practice.

ECMO practical and cognitive skills development

The same survey revealed that less than 50% of these responding US-based ELSO centres (n=43) had an established ECMO simulation programme, and most of them had only been established within the previous 2 to 5 years.(24) Deliberate and repetitive practice of ECMO related skills is critical to patient safety and is expected to improve outcomes, especially when it is employed in an interprofessional simulation context (enhanced by debriefing). For example, SBE had been demonstrated to reduce ECPR times in real patients.(25) Furthermore, cohesion in terms of teamwork performance and knowledge development is generally achieved through interprofessional team training as it can enhance the collaborative working culture and mutual support, which ultimately benefits patient care.(26-28)

The acquisition of ECMO related practical and cognitive skills can leverage on various simulation modalities ranging from screen-based simulators such as ECMOjo to perform various tasks individually (<http://ecmojo.sourceforge.net/>), to using part-task trainers and even more rudimentary equipment to practise technical skills and conduct water drills, through to the use of full-body computer controlled patient simulators to deliver more immersive scenarios with other team members and exercise team behaviours.(29-31) The more technologically advanced simulation approaches are not necessarily the best or most effective as some elements can be distracting to the learners, and hence the choice should be first based on the intended learning objectives.(32, 33) This is where, for example, low-tech water drills (Figure 1), usually done outside

of any contextual scenario, are useful to enhance circuit-related practical skills, but bear little relevance to enhancing critical thinking and decision making skills. To address higher level skills, the focus on the realism might be more concentrated on the presentation and condition of the “patient” via observable physiological or ECMO circuit parameters. ECMO training programmes, such as the ones being conducted in Qatar addressing Respiratory ECMO, ECMO Transport, and Cannulation, are all multidisciplinary to recreate more realistic teamwork interactions and promote collaborative working. They are generally delivered over two days using various approaches such as didactic lectures, demonstrations, skills stations, and immersive scenario-based simulation. Such variety of training approaches allows for a progressive degree of complexity and realism as the learners acquire and develop their ECMO-related skills. Figure 2 shows the observers’ display of a team responding to an immersive simulated ECMO emergency where the focus of the realism is on the patient, the ECMO circuit, and the team as opposed to the room environment.

Adequate preparation of learners before any practical activity is important and initial supervision is normally recommended before they can be encouraged to practise skills on their own or without expert supervision and feedback, so as to decrease the of risk learning improper techniques. More advanced simulation approaches also require some form of learner briefing to establish a safe psychological context and clarify aspects of engagement into the SBE activity.(34)



Figure 1: Water drill station for de-airing during a respiratory ECMO course (Picture courtesy of Abeer Ahmed, with kind permission from Ijaz Hidayat)

Figure 2: Example of multidisciplinary scenario conducted during a respiratory ECMO course.



ECMO simulation fidelity

There are potential risks to SBE that are negative learning, inauthenticity-in-learning, and over reliance on participants’ suspension of disbelief through the “fiction contract”.(35) This is especially relevant to ECMO SBE as circuit/patient interactions are difficult to fully simulate without confusing circuit alterations. Although some studies demonstrate improved patient outcomes following the adoption of a training programme,(36) there are several confounding factors including increasing experience of the team and general development and improvement of the ECMO programme over time. With that regard, both tighter ECMO simulation recommendations and technological developments making simulation more affordable are

realistic in some aspects might help ultimately further improve patient outcomes. “Tighter recommendations” should be understood as complying closely to recently developed simulation education standards, especially in the areas of simulation design, facilitation, interprofessional education, participant evaluation, and debriefing to ensure quality SBE.(37-41)

Several aspects of the level of realism provided to ECMO simulation participants can be critical to them properly understanding how to handle ECMO emergencies and transfer the learning to the real clinical environment.(33) There is however currently no patient simulator that allows for the full scope of ECMO simulation procedures from preparation and pre-cannulation through to operating the ECMO circuit, or even transitioning from VV-ECMO to Veno-Veno-Arterial (VVA) ECMO or dealing with the full range of potential patient or circuit complications.(24, 32)

Our thinking and efforts focus on making ECMO simulation easier and more realistic in order to reduce the current gap between SBE and real ECMO patient care. Issues to be overcome include controlling the circuit pressures, system failures, patient issues, blood colour change, and cost factors. The ECMO machine and consumables are expensive commodities usually and rightfully reserved for patient care usage as opposed to always being available for training purposes. Key to our current developments are the Hospital-University collaboration and research funding whereby current ECMO training issues have been clearly communicated to engineers so they could develop appropriate and cost-effective solutions.

The realism or level of fidelity of the simulation process is an important design factor to prevent negative learning in relation to ECMO specific characteristics. Real components should be used where it is economically sensible (e.g. tubings), whereas more expensive parts can sometimes be replaced by 3-D printed models performing or emulating their functionality (e.g. oxygenator or pump).

Challenges and proposed solutions to ECMO simulation

In the realm of ECMO, providing a realistic medium that is immersive and interactive for a multiprofessional team can sometimes be challenging as replicating important aspects of the patient /machine interactions that are linked by a circuit which clinicians need to check regularly and closely creates a simulation “technical and educational” challenge that may promote negative learning. Negative learning may occur when learners are asked to ignore abnormalities built into the circuit for simulated pressure control purposes for examples as these may be well or poorly concealed into the mannequin. This may encourage learners to pretend to do a full circuit check, ignore observed abnormalities, and become familiar with such abnormal circuit configurations. Such alterations with the addition of additional ports or extensions into the ECMO circuit are usually required to assist with volume adjustments, injection of air bubbles,(24) or even oxygenation levels when animal or expired human blood is used as part of the simulation.

The commonly faced technical or clinical challenges of ECMO simulation are presented in Table 2 alongside potential solutions that have been developed as part of a collaborative project between a university and a newly established ELSO accredited ECMO centre.

ECMO issues	Educational issue	Proposed solution
Air entry into the circuit leading to air bubble detection and noise around the oxygenator.	Home-made solutions usually involve running a tube with a T connector into the circuit to inject air. Even if installed under the patient simulator chest skin, the tubing going to the person pushing the air in may be seen by learners and confuse them.	Remotely operated audio speaker playing sound of air bubbles in the oxygenator combined with 3-D printed replica of oxygenator with remotely controlled display showing image with air bubbles in the membrane.
Oxygenator clotting.	Home-made solutions usually rely on inserting into the circuit some solution which will occlude the membrane such as shredded pieces of animal liver. As described above, the tubing going to the person injecting the occluding solution may be seen by learners and confuse them and it renders the oxygenator no longer usable.	Remotely operated display that shows either a normal oxygenation membrane or various degrees of clotting.
Pump failure.	An embedded scenario participant may switch off the pump and tell the learners that it has failed and not to try to switch it back ON, or the battery may have been purposefully drained, the machine silenced, and the power cord removed to force learners to eventually practise hand-cranking once it shuts itself OFF.	Remotely operated machine console so it can be turned OFF (Blank screen) even if the power cord is still connected to the power supply or if learner press the On/OFF button.
Hypovolemia and line shattering.	Home-made solutions rely on manual withdrawing of fluid from the circuit using an inline connection to a syringe. A confederate nurse is tasked with oscillating the drainage line using an invisible thread or may continuously clamp and unclamp the section of the circuit before it exits the patient simulator or use a valve to perform that pinching action.	Remotely operated display that shows abnormal pressure values and a linear motion device that oscillates the drainage line on demand.
Blood oxygenation, hypoxaemia, and recirculation.	Home-made solutions are unable to create blood oxygenation colour differential unless animal or expired human blood is used in combination with an additional membrane connected to a CO2 cylinder in the section of the circuit before it exits the patient simulator.	A thermochromic solution is circulated within a circuit that manipulates its temperature, leading to a colour change pre and post-oxygenator and pre and post-patient. The heating or cooling processes can be remotely stopped to create a mono-coloured circuit, simulating hypoxaemia or recirculation.
Different modalities of cannulation (VV, VA, VAV, VVA, Femoral-Femoral (Fem-Fem), Femoral-Jugular (Fem-Jug), with Bi-Caval, dual lumen, or reperfusion catheter.	Homemade solutions are often poorly able to realistically reproduce all the steps of cannulation from choosing the right site of cannulation to the optimal positioning of the cannula, dilation of the initial incision, and connection to the circuit to initiate the ECMO run.	A modified mannequin with 3 ultrasound (US) compatible sites (For right jugular and bilateral femoral cannulation) with different anatomic and US characteristics of vein and artery allowing for the Seldinger technique, stepwise dilatation, bleeding control of the pressurised venous and arterial system with laminar and pulsatile flow, cannulation insertion, and positioning around ultrasound compatible heart model, flushing and cannula connection to the circuit with initiation of ECMO run.

Table 2: ECMO issues that are challenging to simulate and proposed solutions.

A prototype ECMO simulator has been developed that allows for realistic ECMO SBE (Figure 3). The system emulates the ECMO machine interface with remotely controllable simulated pressure parameters, haemorrhaging, line chattering, air bubbles noise, and “blood” colour change.(42) The development is at a functional prototype stage, but further technological improvements are still ongoing. Instead of physically simulating some of the issues as is traditionally attempted, some of them have been emulated such as air embolism with associated pump noise and the readings of the pressure sensors and other parameters. These are all displayed on a replica interactive touch-screen ECMO machine console and controllable via a mobile instructor application, whereas ECMO machine settings remain directly controllable by the learners on that console. Oxygenation observable by blood colour change and line shattering caused by access insufficiency are some of the physically simulated issues relying on additional hardware that is currently partially dissimulated inside the custom designed patient simulator.(43, 44) This simulator requires no specific learner orientation, as it fully replicates an actual ECMO circuit and machine, and minimal training for the facilitator operating the instructor application. Although currently modelled around a particular ECMO machine, 3-D printing and reprogramming of the console would enable the system to replicate other types of ECMO machines.

The instructor application will be undergoing further developments enabling it to facilitate uniform scenarios that can be pre-programmed without fewer manipulations required from the facilitator during an actual scenario as it will take into account possible interventions to choose from to update the course of the scenario development based on the actual learners’ interventions. Some of these pre-programmed responses may be automated and based on learners’ input into the emulated yet interactive touch-screen ECMO console, as would be the case if they reduce or increase the pump flow rate. The advantages of such type of applications are the reproducibility of scenarios, a more objective assessment of the learners, and more time for the facilitator to concentrate on the learners as opposed to having to constantly reset all required parameters manually during a scenario in response to learners’ interventions. Further developments might adopt yet a different approach, focusing on independent learning through via serious gaming as a preparatory stage before taking part in a fully immersive simulation session as we have been concentrating on so far to develop problem solving and team working skills.

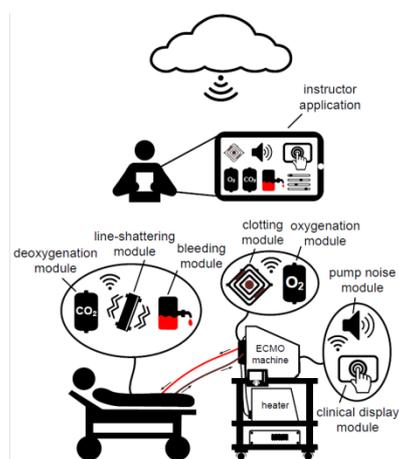


Figure 3: Block diagram of the prototype ECMO simulator developed in Qatar.

Another phase of this collaborative project will focus on embedding the above system with a more comprehensive and custom-designed ECMO patient simulator with integrated cannulation modules linking into pressure controllable pulsatile and laminar flows simulating the arterial and venous circulatory system. The additional training features it will offer include bilateral internal venous and arterial jugular and femoral cannulation under ultrasound guidance, as well as visualization of guidewires and cannulae advancement in the Superior (SVC) or Inferior Vena Cava (IVC)-right atrium junction and iliac artery till their optimal positions in the chest thanks to an ultrasound compatible anatomical heart gel block. The overall system will then allow the complete simulation of an ECMO case with all the possible associated complications.

Discussion

ECMO circuit emergencies are fortunately rare but can be associated with significant patient harm and mortality. Given their rarity, there is a need to ensure ECMO team competency to handle these infrequent occasions. Akin to the management of difficult airways, SBE offers the best available option to provide training in the management of ECMO troubleshooting and emergencies in a safe environment.

Significant advancements and developments in the ECMO technology has led to the expanding use of ECMO therapies worldwide. The increase of utilisation of this expensive lifesaving technology has not yet been met with advances in the directly related simulation technologies by the main equipment manufacturers as it still represents a relatively low volume and niche market over more widely utilised clinical procedures for which clinicians require skill development and advanced simulators have been developed. Trying to fill this gap, several ECMO centres are actually working on developing their own ECMO patient simulator by modifying commercially available mannequins or designing it from scratch.(29, 42, 45, 46) These initiatives sometimes lack expertise in some specific aspects and international collaboration could help advance this niche simulation domain. ELSO is probably the best placed organisation to facilitate such collaborations through a network. It could gather ideas and resources to avoid duplications and save time and efforts. Some of the simulation developments in Qatar can in fact be attributed to the relationships built within the ELSO network.

The key challenges during ECMO simulation are the cost associated with using an ECMO circuit and the oxygenator, the simulation of patient-ECMO interaction without the need for additional connections to the circuit which could lead to negative learning, and finally the difficulties in simulating colour difference in the tubing between oxygenated and de-oxygenated blood. Although animal or expired blood products can be used, they present significant infection control issues.

One of the eight critical factors in creating a successful simulation programme is the "systems: refers to the need to match fidelity requirements to training needs and ensure that technological infrastructure is in place"(47). In the ECMO field, this can be achieved by using the available resources. In our case, a collaborative relationship between medical and non-medical professionals (Electronic and mechanical engineers, computer scientists, simulation experts, and other specialties) have worked together to develop a new system to match the specified learning

objectives. The goal is to make the simulation as realistic as possible, yet cost effective, reusable, upgradable, reproducible, and user friendly to ensure sustainability as equipment used in hospitals evolves over time and the learner and educator workforce are mobile.

Conclusions

The training of ECMO teams using various simulation modalities is playing an increasingly important role but is still at a developmental stage when it comes to recreating immersive scenarios involving circuit or patient issues. The prototype simulator developed in partnership between the authors' academic and hospital institutions allows the simulation of common ECMO emergencies through innovative solutions that enhance the fidelity of ECMO SBE and reduce the requirement for suspension of disbelief from learners. Future developments will encompass the patient cannulation aspect and hence allow for the creation of more longitudinal scenarios. Collaboration, networking, and specific meetings addressing all of these challenges are needed through an international and recognized framework under the aegis of ELSO and will surely stimulate and this field of practice.

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